Augmentation of the Neutronic Safety Aspect of High-Density Fuel Research Reactor Using New Control Element Design

Mohammad Hadi Porhemmat*, Mostafa Hassanzadeh, Aref Rahimian

Reactor and nuclear safety school, Nuclear Science and Technology Research Institute (NSTRI), P.O. Box: 143995113, Tehran, Iran

Abstract

The development of research reactors is expanding to make this industry more economically viable in various fields. One of these areas involves increasing the density of fissile material in fuel. This research emphasizes the importance of paying attention to fuels with a high density of fissile material by examining the silicide plate fuel for core arrangement. The study introduces a new idea and design to enhance two neutronic safety design criteria, specifically the Power Peaking Factor (PPF) and Stuck Rod Shutdown Margin (SRSM) for a standard 10 MW research reactor. Increasing the number of irradiation boxes in the core center results in the maximum flux being distributed over a larger area, reducing PPF. Additionally, leveraging the high moderating ratio of D_2O and, in a new design, using a thin layer of D_2O in the control assembly has raised the worth of the control rod, allowing for reactor control without the need to increase the amount of absorbent material. Moreover, the results of the reactivity coefficient calculations confirm that the implementation of heavy water within the control assembly does not detract from the overall safety of the reactor system.

Keywords: Neutronic Safety Margin, High-Density Fuel, Power Peaking Factor, Stuck Rod.

1. Introduction

Today, the cost-effectiveness of the nuclear industry is a fundamental question that needs to be addressed based on the required output from this sector. Investors in the nuclear industry are particularly focused on the economic viability of research reactors, which play a crucial role in nuclear applications. One of the industry's key challenges is the selection of nuclear fuel as the primary basis for nuclear energy production. As a result, research has focused on developing fuels with low enrichment and higher density of fissile materials, emphasizing peaceful applications and preventing the proliferation of nuclear weapons.

It is important to note that most research reactors for testing materials operate at high power levels (≥10 MW). The primary objective in developing new fuels is to achieve higher powers and neutron flux levels over longer operational cycles while enhancing safety measures. Given the increased fissile material density, research reactors exhibit significantly higher power densities (1880 MW/m³) compared to power reactors (260 MW/m³)[1,2].

Due to the higher power density in these types of reactors, it is necessary to select materials with a high heat transfer coefficient. Therefore, aluminum alloys, with a heat transfer coefficient of 180 W/mK, are the primary candidates for the cladding of this fuel compared to zinc alloy, which has a heat transfer coefficient of 10 W/mK.[3].

Since fuel temperature significantly affects reactivity fluctuations, in a high-power density research reactor, the heat-producing volume should have a smaller thickness to achieve a uniform thermal profile in the fuel volume. This is achievable with plate fuel, which is easier to design due to aluminum's good malleability.

As shown in Table 1, the trend towards high-density fuels is increasing. Therefore, silicide as research reactor fuel has gained more popularity, especially in reactors with a power of more than 10MW. Approximately 82% of silicide reactors with a power of 10MW use plate-type fuel. It is important to note that silicide plate fuel has the highest utilization per hour per year [4].

Table 1: LEU fuel types used by research and test reactors at thermal power levels equal to and greater than 10 MW

Fuel Type	Enrichment (% U-235)	Geometry	Cladding Type	Thermal Power (MW)
$U\text{-}ZrH_x$	HALEU (1)	Disc (1)	Incoloy-800 (1)	14 (1)
$U_3Si_2\text{-}Al$	HALEU (11)	Plate (9) Tube (2)	Aluminum[a] (11)	125(1) 60 (1) 45 (1) 30 (4) 20 (2) 10 (2)
UO_2	6% (2) 4% (1) 3% (1)	Rod (3) Disc (1)	Zirconium[b] (2) Stainless Steel (1) Graphite (1)	200 (1) 30 (1) 25 (1) 15 (1)
$U_3O_8\text{-}Al$	HALEU (3)	Plate (3)	Aluminum[a] (3)	22 (1) 20 (1) 10 (1)
$UO_2\text{-}Al$	HALEU (3)	Tubes (2) Plate (1)	Aluminum[a] (3)	10 (3)
U	NU (1)	Rod (1)	Zirconium[b] (1)	100 (1)
MOX	18% (1)	Rod (1)	Unknown (1)	140 (1)
$U_3Si\text{-}Al$	HALEU (1)	Rod (1)	Aluminum[a] (1)	30 (1)
$UAl_x\text{-}Al$	HALEU (1)	Tube (1)	Aluminum[a] (1)	10 (1)
UO_2-TRISO	17% (1)	Sphere (1)	Graphite/SiC multilayer (1)	10 (1)
U7Mo-Al	HALEU (1)	Plate (1)	Aluminum[a] (1)	15 (1)

[a]Aluminum represents both pure aluminum and aluminum-based alloys
[b]Zirconium represents both pure zirconium and zirconium-based alloys

Also, another noteworthy point shown in Table 2 is the number of working hours of the reactor throughout the year, among which the U_3Si_2-Al fuel has spent the most in the range of operation hours above 4 thousand hours per year [4].

Table 2: LEU fuels in use by research and test reactors operated for greater than 4000 hours per year

Fuel Type	Enrichment (% U-235)	Geometry	Cladding	Utilization (hours/year)	Power (MW)
$U\text{-}ZrH_x$	HALEU (1)	Rod (1)	Incoloy-800 (1)	6000-7000 (1)	14 (1)
$U_3Si_2\text{-}Al$	HALEU (5)	Plate (4) Tube (1)	Aluminum[a] (5)	7000-8000 (1) 5000-6000 (1) 4000-5000 (3)	45 (1) 30 (1) 20 (1) 3 (1) 2.3 (1)
UO_2	HALEU (1) 4%	Rod (2)	Aluminum[a] (1) Zirconium[b] (1)	6000-7000 (1) 4000-5000 (1)	200 (1) 0.04 (1)
$U_3O_8\text{-}Al$	HALEU (3)	Plate (3)	Aluminum[a] (3)	>8000 (1) 5000-6000 (1) 4000-5000 (1)	20 (1) 10 (1) 5 (1)
$UO_2\text{-}Al$	HALEU (1)	Tube (1)	Aluminum[a] (1)	5000-6000 (1)	10 (1)
U	NU (1)	Rod (1)	Zirconium[b] (1)	>8000 (1)	100 (1)
MOX	18 % (1)	Rod (1)	Unknown (1)	5000-6000 (1)	140 (1)
$U_3Si\text{-}Al$	HALEU (1)	Rod (1)	Aluminum[a] (1)	4000-5000 (1)	30 (1)

[a]Aluminum represents both pure aluminum and aluminum-based alloys
[b]Zirconium represents both pure zirconium and zirconium-based alloys

So far, this type of fuel has been used in research reactors with a wide range of power, from kilowatts to 125 megawatts. Silicide fuels with low enrichment and a uranium density of up to 4.8 g/cm^3 are currently being used in 21 research reactors, up to 70 MW, in 13 countries around the world, including France, Australia, and Canada. Technologies have been developed to maximize fuel density by increasing the density of uranium silicide spread on the aluminum matrix to 4.8 g/cm^3 [4].

In the following, some research reactors with U_3Si_2-Al plate fuel are presented. In Reactor Serba Guna–Gerrit Augustinus Siwabessy (RSG-GAS) research reactor, which has a power of 30 MW, the fuel change program from oxide to silicide was started in 1997. In 1998, the design and fuel management strategy for silicide cores with higher uranium loading was carried out. In that research, a new fuel management strategy of silicide equilibrium cores with a higher fuel amount (300 g with a density of 3.55 g/cm^3 and 350 g with a density of 4.15 g/cm^3 per fuel assembly) compared to the previous oxide fuel amount of 250 g and density of 2.96 g/cm^3, investigated. as a result, the cycle length of the reactor was significantly extended [5]. The China Advanced Research Reactor (CARR) with a power of 60 MW has U_3Si_2-Al plate fuel of 19.75% enrichment, encompassing 17 fuel assemblies and 4 hafnium control assemblies which are fuel followers. Also, the reflector of this reactor is heavy water and has a thermal flux of 10^{15} #/cm^2.s in the central channel [6].

The Japan Research Reactor-3 (JRR-3) is a research pool reactor with light water as moderator and coolant, also beryllium, and heavy water role as a reflector. The maximum thermal power of 20 MW using low-enrichment (LEU) silicide fuel plates. The core of the JRR-3 reactor consists

of 26 standard fuel elements, 6 follower fuel elements with neutron absorbers, and 12 beryllium reflectors and is installed at the bottom of the reactor pool [7].

The South African Fundamental Atomic Research Installation (SAFARI-1) research reactor is a pool reactor operating at a nominal power of 20 MW. Its core is cooled by the forced circulation of light water and is also used as a moderator. The core of the reactor is considered with different arrangements of 24 to 32 fuel assemblies [8].

In this research, the advantages of silicide fuel compared to traditional fuels were examined in relation to the neutronic parameters within the core of a 10 MW research reactor. Additionally, the impact of the central irradiation box on key design parameters, such as the PPF and the SRSM, was evaluated. After determining an optimal core arrangement using the diffusion method [10], verification was conducted through the Monte Carlo method. Subsequently, the neutronic feedback parameters, including fuel temperature, coolant temperature, and coolant density, were analyzed for a standard 10 MW reactor core. Furthermore, to ensure the control rod's effectiveness in a new neutronic and safety design, a thin layer of heavy water (D_2O) was examined in various positions near the control assembly absorber.

2. Material and method

Today, due to the high cost of fuel production, there is a shift towards high-density fuels like silicide fuel compared to traditional fuels. This shift results in less waste due to more compact cores, leading to higher flux. The high flux generated allows for a wider range of reactor uses, including the production of various types of radiopharmaceuticals, as well as fuel and materials testing. Therefore, this research has chosen a silicide fuel plate (U_3Si_2-Al) with an aluminum clad. Table 3 provides the necessary material specifications for the SAFARI-1 plate LEU uranium-silicide fuel assemblies. As mentioned in the introduction, a power of 10 MW is taken into account for the neutronic design [8]. Also Figure 1 presents the Standard Fuel Element (SFE) and Control Fuel Element (CFE) configurations.

Table 3: Material specifications for the SAFARI-1 plate LEU uranium-silicide fuel assemblies [8]

Description	Parameter values
Fuel material	U_3Si_2-Al
Cladding and side plate	Al
Uranium density (g/cm^3)	4.8
Fuel enrichment (%)	19.75
^{235}U mass per element (g)	340.1
^{235}U mass per plate (g)	17.9
Total uranium mass per element (g)	1722.0
Total uranium mass per plate (g)	90.63
Number of Fuel Plates Per SFE	19
Number of Fuel Plates Per CFE	14
Meat width, cm	0.0538
Meat length, cm	6.0
Meat Height, cm	60.0
Clad thickness, cm	0.0383
Water channel width, cm	0.2932

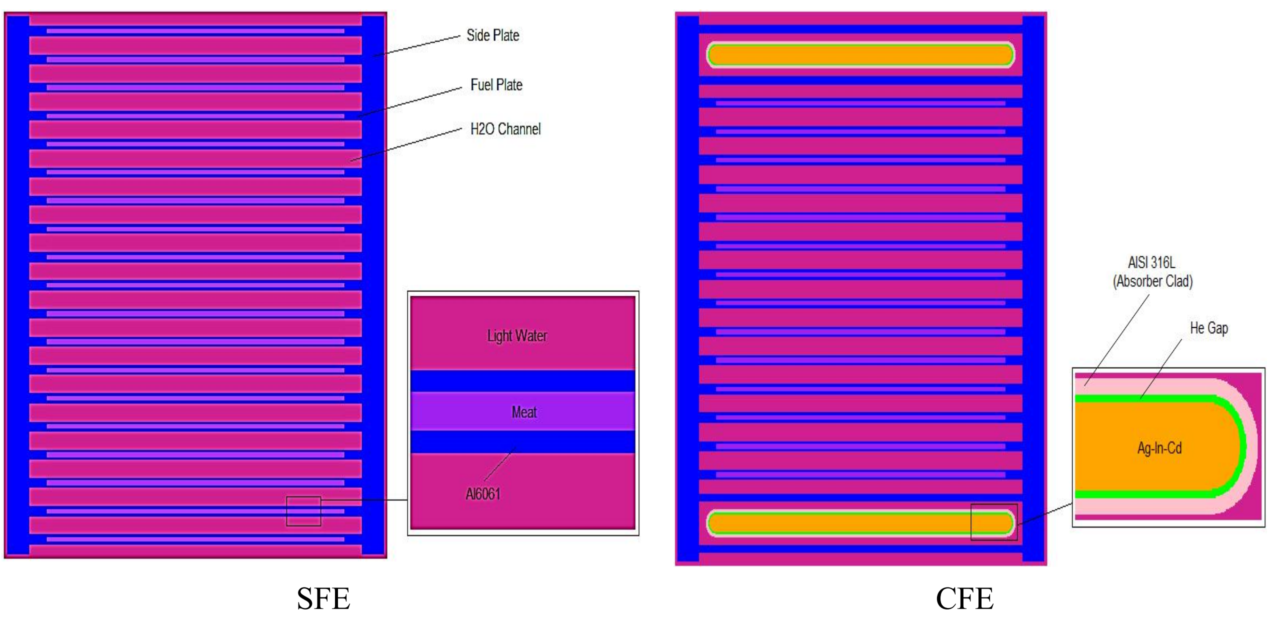


Figure 1: The SFE and CFE configurations

This research investigates the neutronic parameters of a silicide fuel in a 10 MW typical reactor for various core configurations. These parameters include the effective multiplication factor (K_{eff}), excess reactivity (ρ_{ex}) (pcm), shutdown margin (SDM) (pcm), SRSM (pcm), total PPF, integral worth of control rods (IWCRs) (pcm), and safety reactivity factor (SRF). Additionally, the parameters of reactor behavior in both normal and accident operational conditions require an estimation of reactivity changes caused by variations in critical parameters, such as fuel meat temperature, moderator temperatures, density, and changes in moderator density with corresponding temperature.

According to the thermohydraulic criteria for integrating fuel and control assemblies in the core being considered, the most important factors are coolant flow rate, Power Peaking Factor (PPF), and inlet temperature. Therefore, the IAEA proposed a typical 10MW core consisting of 20 fuel assemblies and 5 control assemblies [8]. This research aims to determine the optimal arrangement in a 10MW power core.

In the first step, four different arrangements of silicide fuel were investigated. To achieve high flux, it is crucial to embed the irradiation box in the center of the core. As shown in Figure 2, a core with a central irradiation box was examined by MCNP code. Subsequently, two, three, and four central irradiation boxes were added to the center of the reactor core. The two parameters in neutronic design are the maximum PPF ($PPF<3$) and the maximum value of the SRSM (less than -1000pcm), which determine whether a core is accepted or rejected from a neutronic perspective.

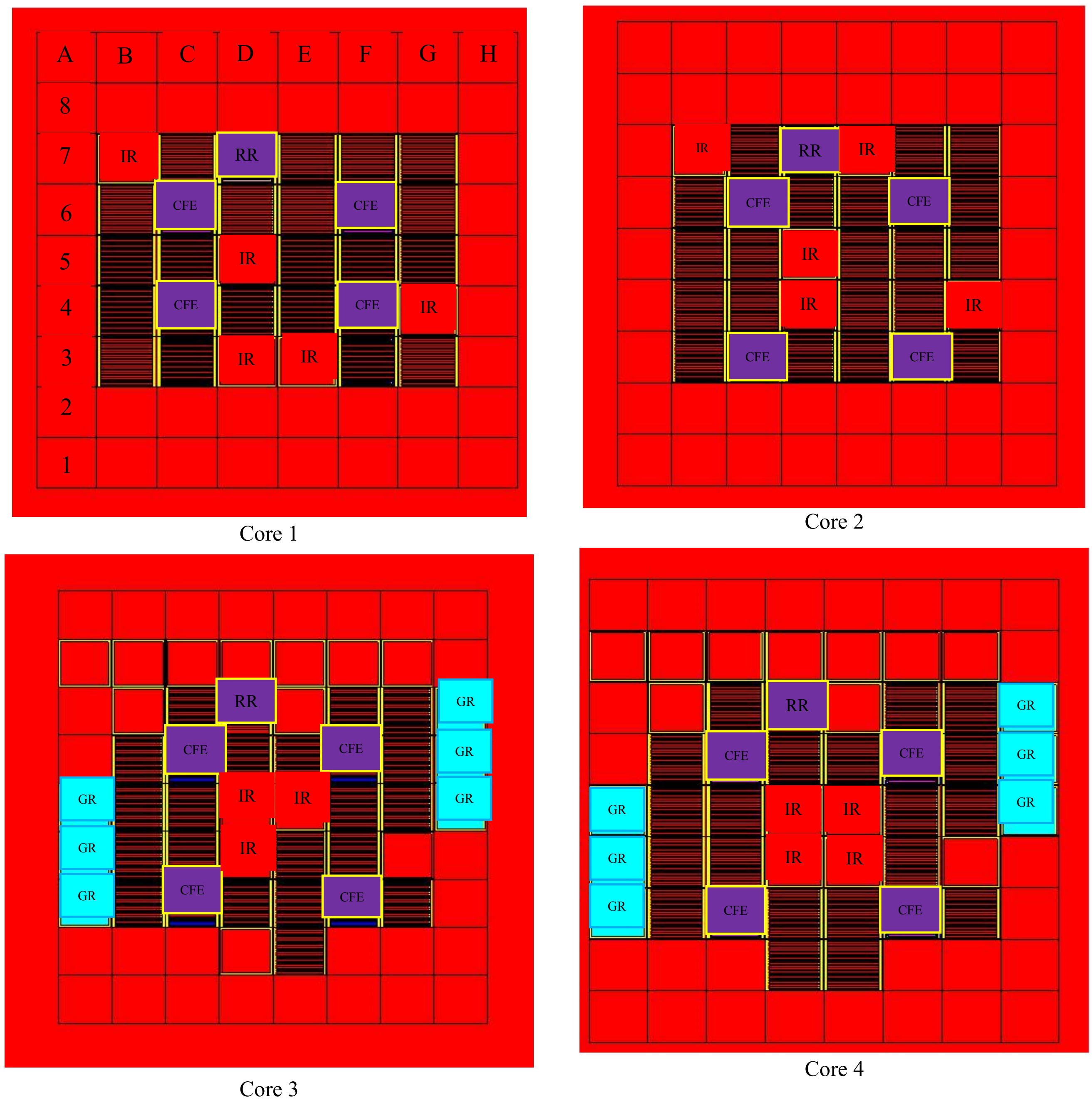


Figure 2: The first core configuration, Core 1: one central box, Core 2: two central boxes, Core 3: three central boxes, and Core 4: four central boxes- (RR=Regulating Rod, IR= Irradiation Box, CFE= Control Fuel Element, SFE=Standard Fuel Element, GR=Graphite box)

3. Analysis and results

3.1 Neutronic parameters calculation

The neutronic parameters of a typical 10 MW reactor for different first core configurations have been investigated. These parameters include K_{eff}, ρ_{ex} (pcm), SDM (pcm), SRSM (pcm), PPF, IWCRs (pcm), and SRF. According to the results in **Table 4**, core No. 4 is better positioned to meet neutronic safety standards than the other cores. Additionally, the worth of the control rods has increased significantly. It should be noted that an important phenomenon that occurs with the increase in the number of boxes in the center of the core is the shift of the neutron flux to the surroundings. This results in a broader distribution of the neutron flux, leading to a reduction in the PPF and an increased flux incident upon the control rods.

Table 4: Neutronic parameters of a silicide fuel of 10 MW typical reactor for different first core configurations

Neutronic Parameters	Core 1 (CIT*)	Core 2 (CIT)	Core 3 (CIT)	Core 4 (CIT)	Core 4 (MCNP)	Core 4 Relative Difference (%)	Safety Criteria
K_{eff}	1.1274	1.0999	1.1021	1.0666	1.0592	0.69	-
ρ_{ex} (pcm)	11301	9081	9262	6247	5585	10.5	-
SDM (pcm)	-5385	-4632	-1533	-5954	-5549	6.8	≤ -3000
SRSM (pcm)	1194	1446	2200	-811	-873	-7.1	≤ -1000
Total PPF	3.2	3.3	3.4	2.95	2.97	0.67	≤ 3.0
SRF	1.47	1.51	1.16	1.95	1.99	-0.02	≥ 1.5

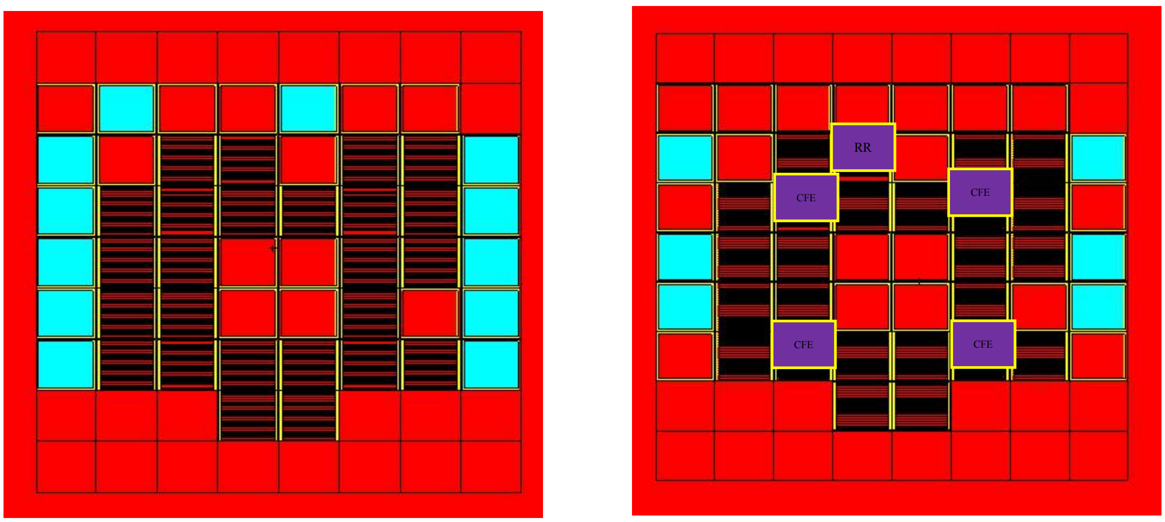
* CIT= CITATION

However, another issue with adding irradiation boxes in the center of the core is the replacement of these boxes with high-reactivity fuel, which presents the challenge of shortening the cycle length. On the other hand, due to the high density of silicide fuel compared to oxide (U3O8-Al), this has less of an effect. Requiring about 3400 pcm for the transition from a cold and clean to a hot state, the 3517 pcm of excess reactivity in the cold and clean states is not sufficient for the core with U3O8-Al fuel, rendering it unable to start a practical cycle (Table 5). Given the requirement for excess reactivity to accommodate experimental programs and to ensure adequate cycle length, the necessary excess reactivity must be appropriately accounted for. Consequently, in the scenario described, only 117 pcm of excess reactivity remains at the commencement of the hot operation, which proves insufficient.

Table 5 : Comparison of Neutronic Parameters of Core 4 Between U_3O_8-Al and U_3si_2-Al

	U_3O_8-Al	U_3Si_2-Al
K_{eff}	1.0365	1.0666
ρ_{ex} (pcm)	**3517**	**6247**
SDM (pcm)	-9825.04	-5954
SRSM (pcm)	-3629	-811

For this purpose, in addition to core number 4 as shown in Figure 3, two other cores, with four irradiation boxes in the center, are examined. It is crucial to note that in the investigation conducted, the excess reactivity and the SRSM must simultaneously meet the desired requirement. In this reactor, the amount of reactivity needed to transition from a cold and clean state to a hot state with xenon is 3400 pcm. Therefore, to achieve the desired cycle length, the excess reactivity of the core at the start of the cycle must be significantly higher than 3400 pcm. Taking into account the excess reactivity and SRSM, two additional cores, 5 and 6, have been included for review alongside core 4.



Core 5 Core 6

Figure 3: The first cores 5 & 6 configurations

Table 6 shows the neutronic parameters comparison results of these two cores [9]. Considering that an increase in the core's excess reactivity decreases the SRSM worth, core number 5 is approximately -1600 pcm away from the design criterion, while this value for core number 6 is about -400 pcm and this difference in worth for core number 4 is -200 pcm. To address this issue, heavy water is utilized around the absorber, as further explained in the following section.

Table 6: Results comparison for first core 5 and 6 configurations

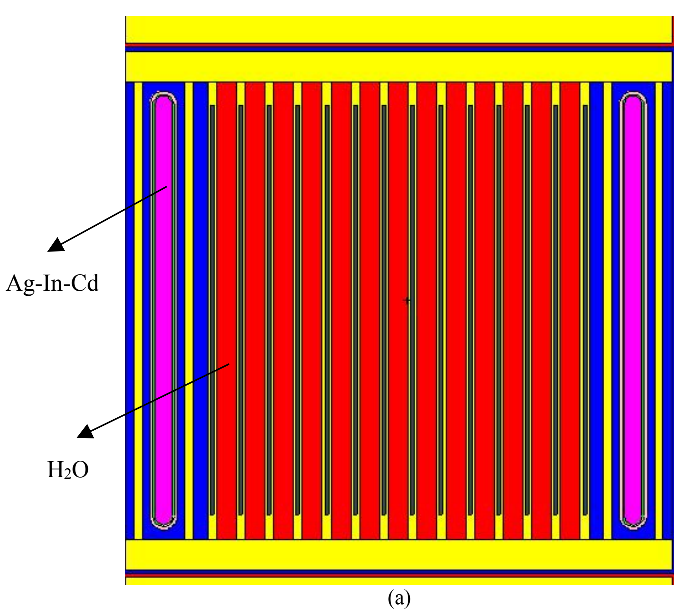
Neutronic Parameters	CITATION Core 5	MCNP Core 5	CITATION Core 6	MCNP Core 6	Safety Criteria
K_{eff}	1.0745	1.0684 ± 0.00060	1.0668	1.0562 ± 0.00054	-
ρ_{ex} (pcm)	6930	6310	6258	5320	-
SDM (pcm)	-5315	-4658	-5959	-5793	≤ -3000
SRSM (pcm)	389	612	-281	-571	≤ -1000
IWCRs (pcm)	-12245	-10968	-12217	-11113	-
SRF	2.3	2.4	2.1	1.9	≥ 1.5

3.2 Effects of D_2O and H_2O moderators on neutronic parameters

In this research, heavy water is placed around the absorber to observe its impact on the worth of the control plates. When using heavy water instead of light water, two key points should be noted. Firstly, heavy water has a smaller scattering cross-section and a much longer migration length (D_2O (174 cm), H_2O (5.84 cm)) compared to light water. This means that neutrons in a medium containing heavy water require a larger volume than light water to reach the thermal range and induce fission. Therefore, if the desired volume is not proportional to the migration length of heavy water, it can lead to a reduction in excess reactivity in a reactor with a thermal spectrum [11].

The second point to consider is that heavy water has a lower absorption cross-section compared to light water in the thermal energy region. While the use of heavy water may initially seem to increase excess reactivity, the large migration length of heavy water in comparison to the dimensions of the fuel assembly and the reactor core in a typical 10 MW reactor reduces excess reactivity. Conversely, using heavy water as a thin layer next to the control rod, due to its lower absorption cross-section, results in an increase in neutron fluence towards the control rod, thereby increasing the worth of the control rod due to absorption.

Figure 4 displays two configurations where heavy water is used instead of light water around the absorber plate. The two Control fuel element (CFE) structures shown were evaluated in cores with numbers 4,5 and 6 each containing four radiation boxes placed in the center. Table 7 presents the calculated effects of adding heavy water in the control assembly with the two structures. According to the table, the use of D2O increases the rate of neutron absorption by the control rods. Additionally, the SDM and SRSM values increase with the presence of heavy water, ultimately enhancing the safety of the reactor.



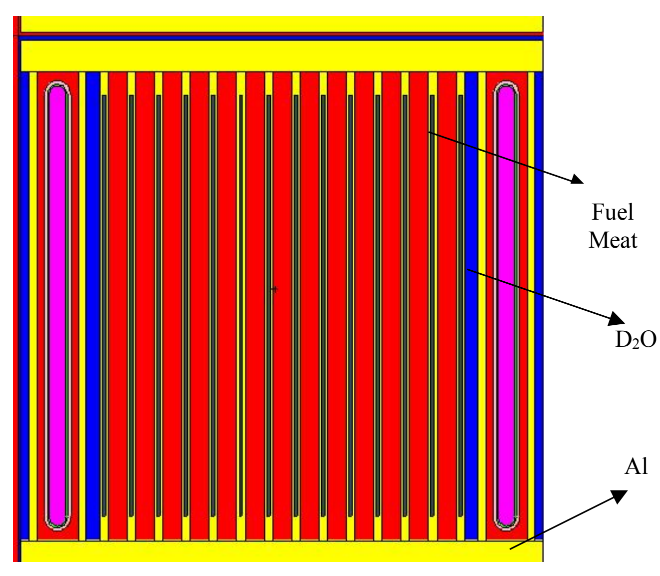


Figure 4: D_2O in two configurations in the control assembly

Comparing these results with the previous state, adding heavy water resulted in an increase of -1000 pcm with structure 1 and an increase of -30 pcm with structure 2 in the worth of control plates in core number 4, for core number 5, it indicates an increase of -960 pcm with structure 1 and an increase of -391 pcm with structure 2, and for core number 5, it indicates a rise of -1052 pcm with structure 1 and an increase of -440 pcm with structure 2.

Table 7: The effect of adding D2O in the CFE with the two Configurations (Figure 4): core 4 configuration

Neutronic Parameters	Configuration (a)	Configuration (b)	Safety Criteria
K_{eff}	1.05215 ± 0.00060	1.05660 ± 0.00057	-
ρ_{ex} (pcm)	4957	5357	-
SDM (pcm)	-6530	-6025	≤ -3000
SRSM (pcm)	**-1825**	**-900**	≤ -1000
IWCRs (pcm)	-11487	-11382	
SRF	1.8	1.9	≥ 1.5

Table 8: The effect of adding D2O in the CFE with the two Configurations (Figure 4): core 5 configuration

Neutronic Parameters	Configuration (a)	Configuration (b)	Safety Criteria
K_{eff}	1.06170 ± 0.00065	1.06609 ± 0.00057	-
ρ_{ex} (pcm)	5811	6199	-
SDM (pcm)	-5425	-4976	≤ -3000
SRSM (pcm)	**-348**	**221**	≤ -1000
IWCRs (pcm)	-11236	-11175	-
SRF	2.2	2.2	≥ 1.5

Table 9: The effect of adding D2O in the CFE with the two Configurations (Figure 4): core 6 configuration

Neutronic Parameters	Configuration (a)	Configuration (b)	Safety Criteria
K_{eff}	1.04965 ± 0.00064	1.05525 ± 0.00063	-
ρ_{ex} (pcm)	4730	5236	-
SDM (pcm)	-6646	-6279	≤ -3000
SRSM (pcm)	**-1623**	**-1011**	≤ -1000
IWCRs (pcm)	-11376	-11519	-
SRF	1.7	1.8	≥ 1.5

Based on the results presented, core number 4 with control structure 1, and core number 6 with control structures 1 and 2 meet the SRSM conditions. With a transition cost of 3400 pcm from cold and clean to hot with xenon state, core number 6 with control structure 2 has the highest excess reactivity for starting hot with xenon state, resulting in a longer cycle length.

3.3 Reactivity feedback

The determination of reactor behavior in both normal and accident operational conditions necessitates an estimation of reactivity changes caused by variations in critical parameters, including meat temperatures, coolant density, and temperature coolant temperature with corresponding density. Using CITATION code, in Figures 5 to 8, reactivity changes are given in terms of state variables for the first core number 4 configuration of light water (H2O) and heavy water (D2O) moderators (structure 2).

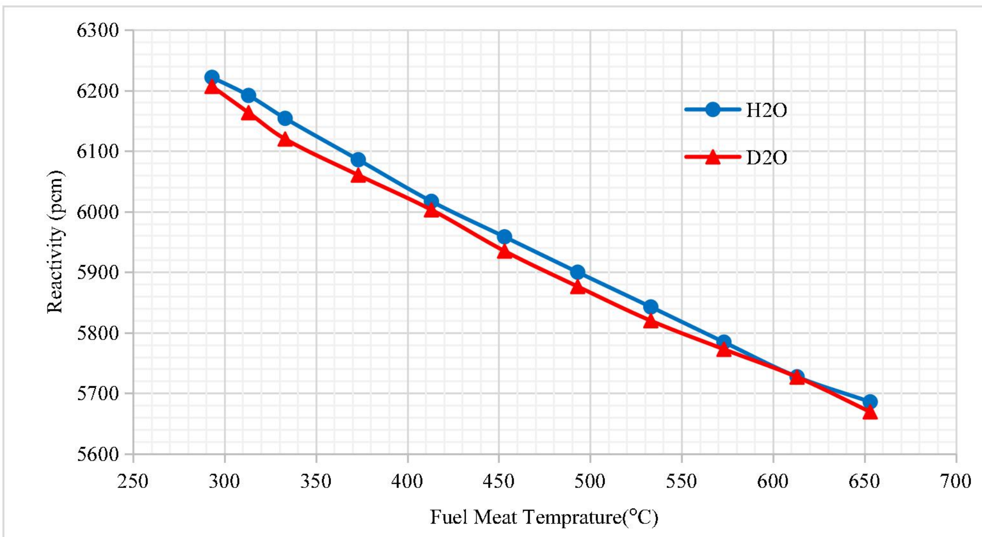


Figure 5: Reactivity variation versus fuel meat temperature

As Figure 5 shows increasing fuel temperature results in a decrease in reactivity due to the appearance of Doppler effects. The results also show that the mean fuel meat reactivity coefficients are -1.51 pcm/°C and -1.56 pcm/°C for H2O and D2O moderators, respectively.

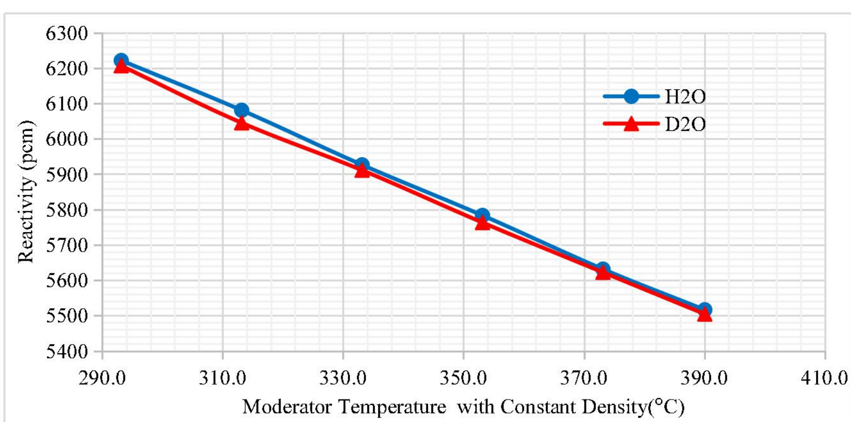


Figure 6: Reactivity variation versus moderator temperature

Moreover, Figure 6 represents reactivity variation versus moderator temperature, with constant moderator density. As a safety aspect, the key takeaway from this figure is that the moderator temperature coefficients with constant density are -7.26 pcm/°C and -7.24 pcm/°C for H_2O and D_2O moderators, respectively.

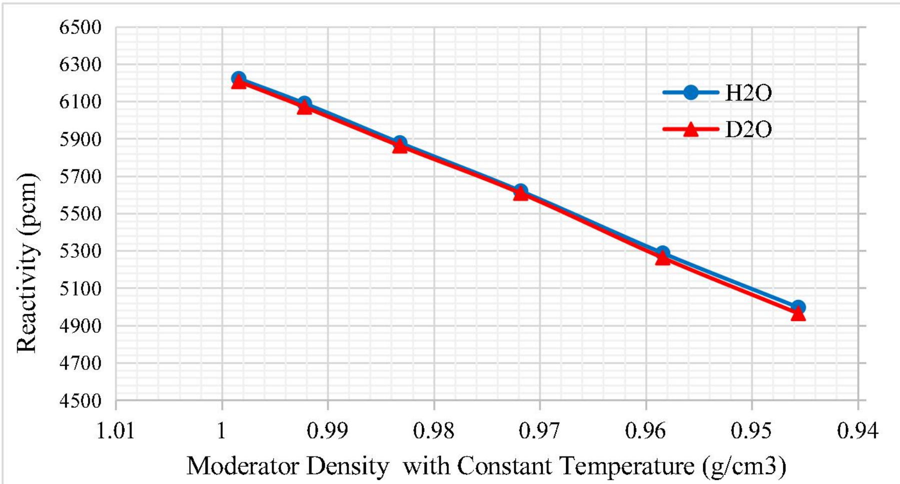


Figure 7: Reactivity variation versus moderator density

To ensure the moderator reactivity coefficient in this step, the effects of moderator density on reactivity variation are depicted in Figure 7. The obtained results confirmed that the moderator density coefficients for H_2O and D_2O moderators are -12.78 pcm/°C and -12.96 pcm/°C, respectively.

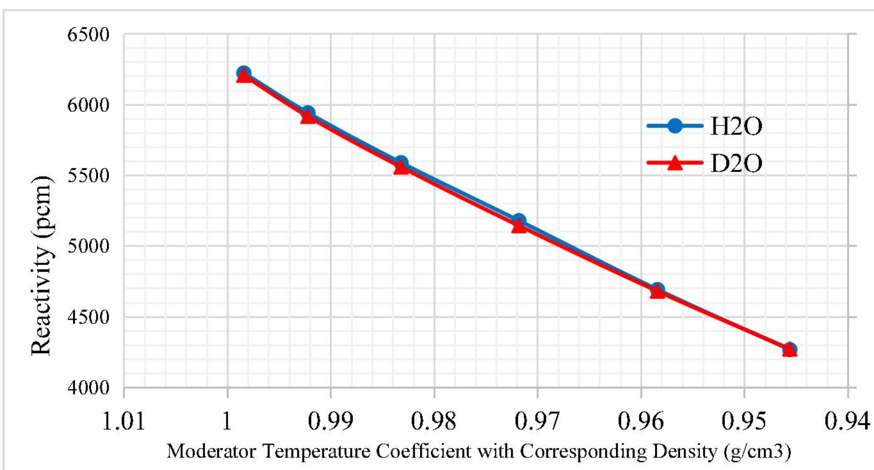


Figure 8: Reactivity variation versus moderator temperature with corresponding density

Eventually, to see the effects of moderator conditions on the reactivity state, density and temperature variation are considered together and depicted in Figure 8. The reactivity coefficients calculated from this step, -20.33 pcm/°C and -20.11 pcm/°C for H2O and D2O moderators, respectively, confirm the reactor's safe configuration.

4. Conclusion

This research focuses on enhancing the neutronic safety design of a typical 10 MW research reactor using high-density silicide fuel. The study investigated the effects of increasing the number of irradiation boxes in the core center and using a thin layer of D_2O in the control assembly, on two neutronic safety design criteria: the PPF and SRSM. In summary, the structure of this research and its accomplishments are outlined as follows.

First, neutronic design criteria and their associated challenges and solutions are investigated.

- **Power Peaking Factor**: The high-power density in silicide-fueled reactors requires smart management of the PPF to avoid excessive heat generation in specific areas. The study found that increasing the number of symmetrical irradiation boxes in the core center distributed the maximum flux over a larger area, leading to a reduction in PPF.
- **Stuck Rod Shutdown Margin (SRSM)**: Meeting the required SRSM criterion of -1000 pcm is crucial for ensuring the reactor can be safely shut down even with a stuck control rod. The study initially found that the SRSM for a core with four irradiation boxes was insufficient. To address this, the researchers investigated using heavy water (D_2O) around the control rod absorber.
- **Increased Control Rod Worth**: D_2O has a lower absorption cross-section than light water, allowing more neutrons to reach the control rod, thus increasing its worth.
- **Enhanced Safety Margins**: The use of D_2O increased both the SDM and SRSM, improving the reactor's safety.

The study analyzed reactivity changes due to variations in fuel temperature, moderator density, and moderator temperature. The results indicate that the reactor configuration incorporating D2O maintains safe reactivity coefficients across all parameters, ensuring stable and controlled operation. The key findings of this research cloud be mentioned as follows:

- **Optimal Core Configuration**: A core configuration with four irradiation boxes in the center and a thin layer of D_2O surrounding the control rod absorber was found to meet the safety criteria for PPF and SRSM.
- **Improved Cycle Length**: The use of D_2O in the control assembly, coupled with the high density of silicide fuel, can contribute to longer operational cycles.
- **Enhanced Safety**: The study demonstrated that incorporating D_2O in the control assembly design can significantly improve the safety margins of a typical 10 MW research reactor using silicide fuel.

In this study, we examined the fresh core, also known as the first core. In our future research, we will be evaluating the equilibrium core with burned fuel starting from the core presented here, for specific applications.

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